Resistive wall mode kinetic stability advancements for refined comparison with experiments

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The resistive wall mode (RWM) instability can lead to disruption of the plasma current in a tokamak. For continuous operation of future devices it is important to understand the physical mechanisms enabling stability of the RWM and to control unstable modes that do arise [1]. A theory for the stability of the RWM that includes kinetic effects arising from perturbation of the distribution function of particles has been developed [2] and successfully compared with experimental results [3-6]. In particular, resonances between thermal particle motions and the plasma rotation can lead to a dissipation of the mode energy while energetic particles (EPs) can provide a restoring force that resists the expansion of the magnetic field. The rotational resonances can explain the experimental observation of RWM stability at low rotation in NSTX [3], while EP effects may explain the difference between stability in NSTX and DIII-D [4,6].

By returning to the derivation of the theoretical model for RWM stabilization and rolling back assumptions, we can produce an expansion of the theoretical model beyond the presently included physics [7]. New terms include anisotropic pressure corrections to the fluid terms, an electrostatic contribution, a centrifugal force arising from bulk plasma flow, and finite Larmor radius effects. Additionally, the treatment of particle collisions is shown to be an important factor in stability [8], and can be further improved. Each of these advancements in kinetic stability theory are investigated using the `MISK` code [2], with the goal of improving quantitative agreement with present experiments in devices such as NSTX, and to use this physics understanding to determine the implications for future devices, such as ITER. Finally, the resulting RWM dispersion relation allows for multiple roots of the instability [9]; these are also investigated.

Anisotropy

Anisotropy of the equilibrium pressure with respect to pitch angle is commonly caused by energetic particles resulting from neutral beam injection. It has been shown that correct treatment of energetic particles as anisotropic rather than isotropic can lead to a reduction of their stabilizing effect, and better agreement between calculated RWM stability and experimentally observed behavior [4]. The main effect is a more accurate portrayal of the division of energetic particles between trapped particles, which contribute more greatly to stability, and circulating particles, which contribute less. A re-evaluation of the theory shows, however, that anisotropy also leads to corrections of most of the usual fluid terms, and to a newly implemented term [7,10]. The fluid term can then be written $\delta W_F + \delta W_A$, where

$$\delta W_A = \frac{1}{2}\int \left\{ (1-\sigma)\left(-\frac{|\tilde{B}_\perp|^2}{\mu_0} - \frac{B^2}{\mu_0}|\nabla\cdot\xi_\perp + 2\xi_\perp\cdot\kappa|^2 + j_\parallel\left(\xi_\perp^*\times\hat{b}\right)\cdot\tilde{B}_\perp \right) - 2B|\nabla\cdot\xi_\perp + \kappa\cdot\xi_\perp|^2 \frac{\partial p_{\mathrm{avg}}}{\partial B} \right\} d\mathbf{V}.$$

Here σ is the usual anisotropy parameter [10]. The final term is the new term, which is examined separately in Fig. 1 for an example case with a Gaussian distribution function for EPs around the beam injection pitch angle $\chi_0 = v_\parallel / v$, and with width $\delta\chi$. One can see that this anisotropic δW term generally becomes more negative (destabilizing) as the EPs become more narrow in pitch. For comparison, the total $Re(\delta W_K)$ was 3.3×10^{-2} for this case, so a value of $\delta W = -5\times 10^{-3}$ represents a $\sim 15\%$ correction, which can improve the already close agreement with experiment.

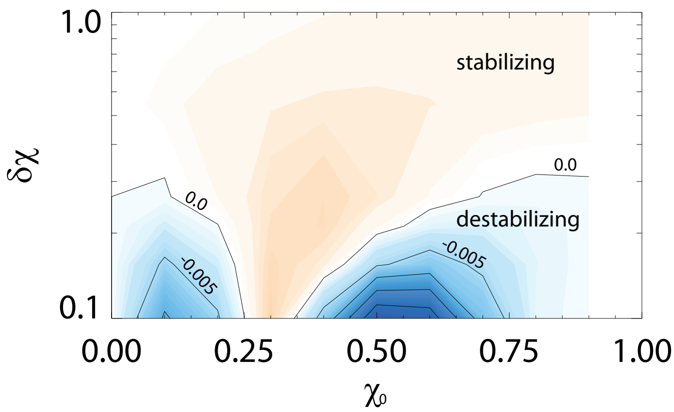

Figure 1: Contour plot of the last term of δW_A vs. injection pitch angle (perpendicular to parallel from left to right) and Gaussian width (more isotropic to more narrow from top to bottom).

Electrostatic Effect

Typically the electrostatic component of the perturbation, $\tilde{\Phi} + \xi_\perp \cdot \nabla\Phi_0$, [2,10] is ignored. By using a quasineutrality condition, however, this quantity can be calculated, and used to calculate the electrostatic contribution to δW [2]. The electrostatic contribution is strictly real and negative definite, so it is generally destabilizing, which generally would improve agreement with experiment. A calculation for a typical NSTX plasma, however, shows that the electrostatic contribution is generally quite small, on the order of 1% of the kinetic term.

Collisionality

Collisions have been shown to have a different impact on RWM stability through kinetic models than through previous models [8]. Specifically, collisions are stabilizing by dissipating the mode energy, but are also destabilizing as they reduce the resonant kinetic stabilizing effects.

When the plasma rotation frequency is away from a stabilizing resonance (with the precession drift or bounce motions of the thermal particles) the net effect is that collisions have little impact on stability. When kinetic rotational resonances are present, however, low collisionality allows them to be even stronger so that future devices with lower collisionality such as ITER may be more stable than present devices, if the plasma rotation is strongly in resonance with thermal particle motion, and there is sufficient energetic particle stabilization as well. Figure 2 shows an example calculation of the RWM growth rate for an NSTX plasma with the experimental levels of rotation and collisionality scaled. When the rotation is in resonance with the precession drift frequency of thermal ions (roughly at $\omega_\phi/\omega_\phi^{\mathrm{exp}} = 0.5$), lower collisionality leads to greater stability; otherwise collisionality has little effect on stability.

Accurately modeling the effect of collisions is important, then, for calculating plasma stability. The difference between collisionless, energy-independent collisionality, and energy-dependent collisionality can be significant [8]. For example the kinetic effects from electrons can be significant in the collisionless case, but are greatly reduced with a proper collisionality model. Further improvements to the collisionality model can be made, including possibly using a pitch-angle dependent Lorentz collisionality, or a momentum-conserving Krook operator.

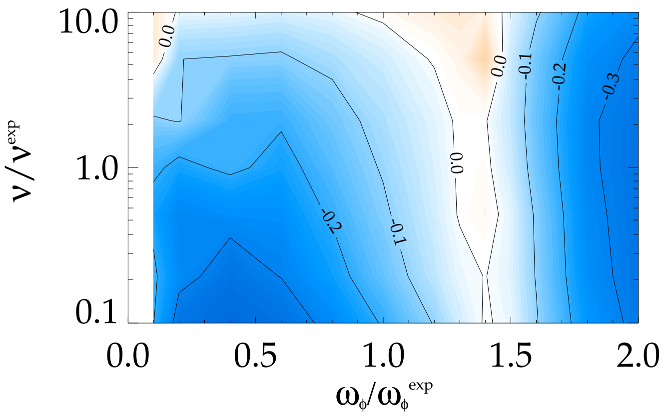

Figure 2: Contour plot of normalized growth rate $\gamma\tau_w$ vs. scaled plasma rotation frequency and collisionality for an NSTX plasma. Blue is stable and red is unstable.

Multiple Roots

The RWM dispersion relation with kinetic effects is cubic, so three distinct modes of instability could simultaneously exist [9,11]. A detailed examination, however, found that only one root has a slow mode rotation frequency [9]. This is the usual RWM mode which is observed in NSTX. The other two modes were found to rotate on the order of the plasma rotation frequency [9]. Moreover, these two rotating modes are damped by ion and electron collisions, respectively, and so are predicted to be quite stable in present devices such as NSTX.

Discussion and Implications for ITER

Future burning plasma devices such as ITER will have a lower collisionality and lower plasma rotation frequency than present devices. Kinetic stability theory provides multiple implications for such a scenario. First, the lower collisionality means that multiple roots of the RWM dispersion relation may be near marginal stability and rotating at moderate frequencies, more like slowly rotating RWMs ($< \tau_w^{-1}$), rather than highly rotating ($> \tau_w^{-1}$), highly damped modes. Second, lower collisionality should also make the RWM more stable when the thermal particles are in a rotational resonance, but may not affect the lower stability when the plasma is off-resonance. This makes it especially important to avoid off-resonance conditions in high β ITER operation, and therefore to accurately understand and predict the thermal particle resonant stabilization. It will also be necessary to have a source of controllable momentum input to reach a favorable rotation profile, and active RWM control to avoid disruptions when the plasma moves away from the resonance condition [1]. Finally, ITER will have both isotropic alpha particles and anisotropic energetic particles from neutral beam injection. Calculations including alpha particles but not energetic ions showed that ITER, with the expected level of plasma rotation, will be unstable once the plasma makes an excursion above the no-wall limit and must rely on alpha particles to stabilize the plasma [4]. EPs are expected to be stabilizing, but accurately computing the degree of stabilization will depend on the inclusion of anisotropic corrections in the theory. Advancements in kinetic RWM stability theory are being implemented in present calculations and compared to experimental results on NSTX to refine quantitative agreement and increase confidence in extrapolation to future devices.

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